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USE OF VLBI MEASUREMENT TECHNIQUE FOR DETERMINATION OF MOTION PARAMETERS OF THE TECTONIC PLATES

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Abstract

Modern space measurement techniques like SLR, DORIS, VLBI and GNSS are used to study the tectonic plates. The determination of plate motion parameters (Φ, Λ, ω) from various geodetic measurements is outlined. This paper is the third part of our studies on estimating geodetic and geodynamic parameters; it regards an accuracy analysis of the determined Φ, Λ, ω parameters which describe motions of the tectonic plates using *Very Long Base Interferometry* (VLBI) technique. Prior to this, SLR and DORIS space measurement techniques were examined by authors. The study is based on the velocities of station positions, as included in a realization of the *International Terrestrial Reference System* – ITRF2008 for VLBI technique, published by the International Earth Rotation and Reference Systems Service (IERS). This model is made subject to an analysis in association with the APKIM2005 model. Six big plates, namely: Eurasian (EUAS), African (AFR), Australian (AUS), North American (NOAM), Pacific (PACF) and Antarctic (ANTC) were analysed. The results obtained in this analysis were compared with our previous estimations based on DORIS and SLR techniques and estimated according to the APKIM2005 model. Generally, all our three solutions based on SLR, DORIS and VLBI measurement techniques were found to be consistent.

Keywords: Very Long Base Interferometry measurement technique, plate tectonic, plate motion parameters, ITRF2008.

1. Introduction

Estimation of tectonic plate motion has become an important field of geodesy for numerous reasons. One of them is estimation and monitoring in time of station positions on the Earth with an accuracy as high as a few millimetres. The geodetic measurements with DORIS, SLR, VLBI and GPS techniques have been used to determine horizontal motion of the Earth's surface with a high accuracy. All the above-mentioned satellite data enable to improve satellite orbits, geophysical parameters and, ultimately, station coordinates and velocities. As the final results, station positions are estimated with an accuracy of 2–3 millimetres.

This paper constitutes the third part of a series dedicated to analysing the estimation of tectonic plate parameters on the basis of the above-mentioned measurement techniques. This part is applicable to the Very Long Baseline Interferometry. The IERS has provided a series of *International Terrestrial Reference Frames* (ITRFs) and described parameters (station positions and velocities), which are dynamically and constantly refined. They can be used in the research on crustal movement and geodynamics. In our solution station positions and velocities are taken from ITRF2008 estimation at epoch 2005.0 [1, 2]. The ITRF2008 model is in agreement with NNR-NUVEL1A, which is constructed on the basis of geophysical and geological data. It is a version of the ITRF based on the combined solutions for four measurement techniques (GPS, DORIS, SLR, VLBI) stretching over, respectively, 29, 26, 12.5, 16 years of data [1]. The network of ITRF2008 consists of 934 stations with their 580 location sites, 463 of which being located in the northern hemisphere and 117 in the southern one. All mentioned techniques enable to estimate station positions with accuracies of about 1–3 mm and velocities – of 1 millimetre per year. It is described by Ze *et al.* [16]. The satellite measurements create a database which is used for computation of different quality and quantity station positions and velocities (the results are based on different numbers of measurements, different time intervals and different accuracy of measurements). The observation (3) used in the solution and multiplied by weights of measurements agree with ($P = 1/m^2$) which are functions of the measurement accuracy and the number of measurements. It is the authors' idea to determine motion parameters of tectonic plates with the application of the mentioned measurement techniques separately and to compare the obtained estimation results. In the previous papers: Kraszewska *et al.* [10] and Kraszewska *et al*. [11] the SLR and DORIS techniques were scrutinized. This paper deals with the VLBI network.

2. Brief presentation of VLBI measurement technique

The VLBI is included in the group of cosmic measurement techniques. For the last ten years, with a sizeable growth in the number of VLBI antennas all over the world, new stations have been built in various countries. The primary reason behind this increase stems from the technical development, which brought about a considerable improvement in quality of the obtained results. In short, in 1980 the range of error of station position was of a decimetre order and a few centimetres for the station displacement velocity per year [13], in the early 1990s the range of position error was at a level of centimetre and less, whereas the error in for velocity was of an order of a few millimetres per year. Currently, the accuracy is of an order of a few millimetres. Unfortunately, the distribution of antennas is not uniform worldwide. The majority of antennas are located in the northern hemisphere, specifically in such areas as the western part of North America, Europe, Japan and China [3], whereas stations with VLBI telescopes are sparsely distributed in more remote areas, including Antarctica (two stations), Africa (one station), Australia (three stations). The VLBI measurement technique provides the definition and monitoring of geodynamical effects: EOP, variable Earth rotation, polar motion, Earth tides, station positions and velocities, and crustal deformation. In the VLBI technique, signals from quasars are collected by multiple antennas distributed over the Earth. The distance between radio telescopes is calculated using the time difference between the arrivals at two Earth-based antennas of a radio wave front emitted by quasars. Relative changes in the antenna positions from a series of measurements indicate tectonic plate motion. The distance between telescopes is measured using a time delay τ of the signal reaching two antennas located several thousand kilometres apart. The time delay is calculated as:

$$\tau = \frac{1}{c} u \Delta r, \tag{1}$$

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where: c – a speed of radio signal; u – a unitary vector of radio source; Δr – a distance between two telescopes.

Stability of measurement depends on the distance between the antennas and the accuracy of measurement time.

3. Estimation of tectonic plate motion parameters

Usually, for estimation of the plate motion parameters and station positions and velocities, a few techniques are used, *e.g*. the one presented by Noomen *et al.* [12]. In the series of our papers we would like to estimate separately the contribution of each technique to the accuracy of the solution. The outer part of Earth is covered by movable plates. The motion of these plates is described by a rotation vector Ω whose representation Λ is the geodetic position of rotation pole Φ, together with rotation velocity ω illustrated by Drewes [5]. It is shown in Fig. 1 [5].

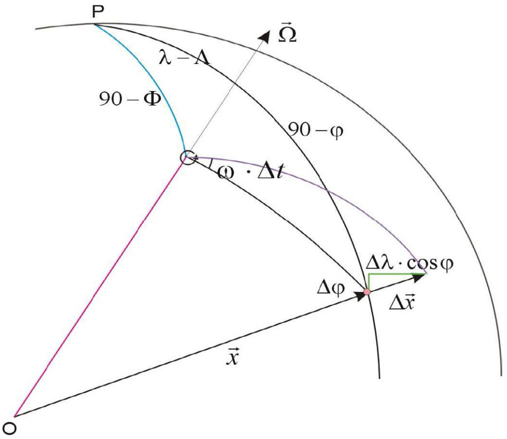

Fig. 1. Relations between the plate motion parameters [5].

Where: φ, λ – define a station position; $\Delta\varphi$, $\Delta\lambda$ – define a displacement of station position; Φ, Λ, ω – define plate motion parameters.

A displacement of station position in latitude and longitude caused by plate motion parameters is expressed:

$$\begin{aligned}\Delta\varphi &= \omega \cdot \Delta t \cdot \cos\Phi \cdot \sin(\lambda - \Lambda),\\ \Delta\lambda &= \omega \cdot \Delta t \cdot (\sin\Phi - \cos(\lambda - \Lambda)\tan\varphi \cdot \cos\Phi).\end{aligned} \tag{2}$$

Observation equations are expressed:

$$\begin{aligned}v_\varphi &= \left(\frac{\partial\Delta\varphi}{\partial\Phi}\right)\mathrm{d}\Phi + \left(\frac{\partial\Delta\varphi}{\partial\Lambda}\right)\mathrm{d}\Lambda + \left(\frac{\partial\Delta\varphi}{\partial\omega}\right)\mathrm{d}\omega - \left(\Delta\varphi^{obs} - \Delta\varphi^{cal}\right)\\ v_\lambda &= \left(\frac{\partial\Delta\lambda}{\partial\Phi}\right)\mathrm{d}\Phi + \left(\frac{\partial\Delta\lambda}{\partial\Lambda}\right)\mathrm{d}\Lambda + \left(\frac{\partial\Delta\lambda}{\partial\omega}\right)\mathrm{d}\omega - \left(\Delta\lambda^{obs} - \Delta\lambda^{cal}\right)\end{aligned}. \tag{3}$$

Tectonic plate parameters can be described using three methods. The first method is based on computation of plate motion parameters (Φ, Λ, ω), the second one – on computation of angular velocities around three axes (ω_x, ω_y, ω_z), described by Van Gelder and Aardoom [15]. The expressions (4) enable to transform the angular velocities to the parameters of plate motion. The third one is a geophysical method based on examination of geophysical phenomena near the plate boundary (not used in this paper).

$$\begin{aligned} \tan\Phi &= \frac{\omega_z}{\sqrt{\omega_x^2+\omega_y^2}} \\ \tan\Lambda &= \frac{\omega_y}{\omega_x} \\ \omega &= \sqrt{\omega_x^2+\omega_y^2+\omega_z^2} \end{aligned}, \tag{4}$$

where:

$\frac{\partial\Delta\varphi}{\partial\Phi}, \frac{\partial\Delta\varphi}{\partial\Lambda}, \frac{\partial\Delta\varphi}{\partial\omega}$ – matrix A of partial derivatives for observation equations;

$\frac{\partial\Delta\lambda}{\partial\Phi}, \frac{\partial\Delta\lambda}{\partial\Lambda}, \frac{\partial\Delta\lambda}{\partial\omega}$

$\Phi_0,\ \Lambda_0,\ \omega_0$ – initial values of Φ, Λ, ω;

$\Phi = \Phi_0 + \mathrm{d}\Phi$,

$\Lambda = \Lambda_0 + \mathrm{d}\Lambda$ – corrections for $\Phi_0,\ \Lambda_0,\ \omega_0$.

$\omega = \omega_0 + \mathrm{d}\omega$.

The Φ, Λ, ω parameters constitute are functions of a station’s yearly shifts. The least squares method makes it possible to determine the values of Φ, Λ, ω parameters from the shifts of chosen stations, as it is presented by Drewes [4] and in our previous paper [10].

A sequential method consisting of a few steps was adopted for the analysis. To estimate tectonic plate parameters there are necessary two or more stations located on each of the plates. It enables to construct observation equations and adjust three unknowns of plate motion parameters. In the first stage, the parameters of tectonic plates for two stations located on a plate are adjusted. Selecting these first two stations is very important; the distance between them has to be equal to 60–70% of the distance between boundaries of the plate and cannot be smaller than 50–100 km. The stations have to be located in a stable region, not in a cracked region near the plate boundary. For all stations, an even distribution of station positions for each tectonic plate is recommended. A dense concentration of a high number of stations over a small-size area does not result in a significant improvement of solution accuracy. In the next step of calculations, new stations are one after another included into the solution. A few of the stations which cause a large error or due to an increase of error values are rejected. In each stage, the Φ, Λ, ω parameters are made subject to the second adjustment in view of making their stability and errors observable. It is depicted in Figs 4a, 4b, 4c for the EUAS plate, 5a, 5b, 5c for the NOAM plate and 6a, 6b, 6c for the PACF plate. The situation when a change of a determined value in the successive step is smaller than the value of error of the solution enables to observe the solution stability.

In the paper there are analysed the final adjusted Φ, Λ, ω parameters. The estimated values for each plate and each step are shown in Tables 1–5 for the EUAS, NOAM, PACF, AUS and ANTC plates, respectively. A similar method of adjustment for the DORIS, SLR and VLBI is used and described extensively in Kraszewska *et al.* [10] and Kraszewska *et al.* [11]. A block diagram of the adjustment of the plate motion parameters is shown in Fig. 2. Our own software in FORTRAN90 was used to carry out the computations.

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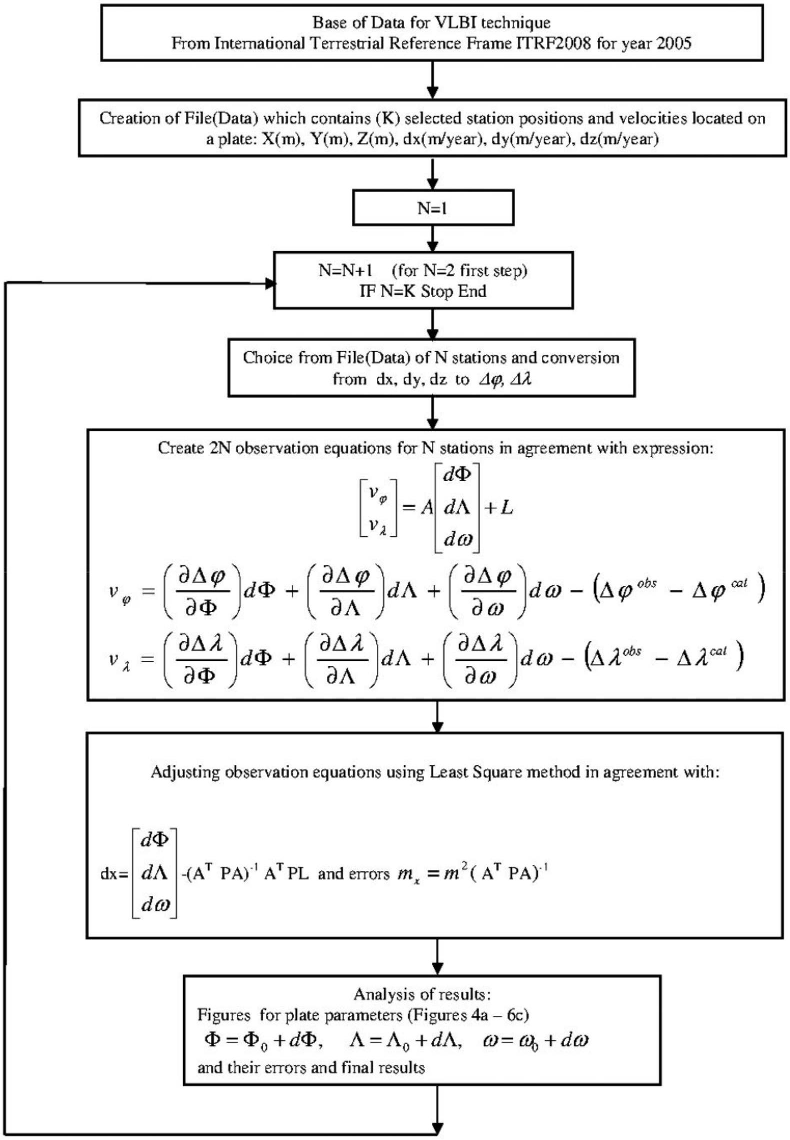

Fig. 2. A block diagram of the method of estimation of Φ, Λ, ω parameters.

4. Results

In the paper there are presented the results of estimation of Φ, Λ, ω parameters from the velocity vectors shown for selected stations located on the EUAS, NOAM, PACF, AUS and ANTC plates. The authors' objective of this research is to demonstrate the impact of the location and number of stations on the determination accuracy of Φ, Λ, ω parameters in the case of using the VLBI measurement technique for each plate being analysed. In Table 6 the obtained results are compared with those achieved with the APKIM2005 model by Drewes [6]. This model, similar to our solution, is based on four techniques: VLBI, GPS, DORIS, SLR. For GPS technique the data were collected from 1996 to 2005, for VLBI – from 1981 to 2005, for SLR – from 1993 to 2005, and for DORIS technique – from 1993 to 2005. Satellite orbits were estimated for GPS, SLR and DORIS in weekly periods; only for VLBI technique – in daily sessions. The following parameters were estimated: station positions, velocity, EOP and mass centre of the Earth. Our computations were performed using station positions and velocities from the ITRF2008 for VLBI technique [1]. The φ, λ, h coordinates for VLBI telescopes were transformed from the X, Y, Z coordinates. It is described by Heiskanen and Moritz [8].

The VLBI network is not uniformly distributed throughout the Earth's surface. Most of stations are located on the northern hemisphere, especially on the EUAS and NOAM plates. Globally, the number of stations taken for the solution amounts to approx. 65, and it is the number similar to that used in SLR and DORIS techniques. However, their locations are completely different. In the northern hemisphere areas, such as: North America, Japan, China and Europe more telescopes are placed, while in the southern hemisphere the number of VLBI antennas is very small: Antarctica (two stations), Africa (one station), Australia (three stations). It is due to the possibility of monitoring only three big plates with a great number of telescopes.

For the EUAS plate 19 stations were used in the analysis: Ny Alesund (7331), Svetloe (7380), Medicina (7230), Urumqi (7330), Shanghai (7227) Mizusawa (7314), Shintotsukawa (7346), Matera (7234), Simeiz (7332), Zelenchukskaya (7831), Madrid (1565), Trysil (7607), Onsala (7213), Metsahovi (7601), Effelsberg (7203), Wettzell (7224), Badary (7382), Yebes (7333), Noto (7247). As shown in Fig. 3, as many as 14 of these stations are located in Europe. Five stations are placed in Asia; two of them – Badary and Urungi – are located in an unstable region. In the European part of the plate, four stations are in the North of the continent, four in the central area and six stations in the southern area. The northern part – Svetloe, Ny-Alesund, Metsahovi and Onsala are dominated by the postglacial isostatic rebound [7]. Since approximately 10,000 years ago, the area in question has been permanently elevated with respect to the central part of the EUAS plate. The collision of the AFRC plate with the EUAS one results in the motion of VLBI antennas being pushed in the southern part of Europe. [9]. The movement of the stations in the central part is stable, as it is shown in detail by Tomasi *et al.* [14]. The stations Yebes and Zeluenchukskaya have velocity vector errors larger than 1 mm per year, especially for the

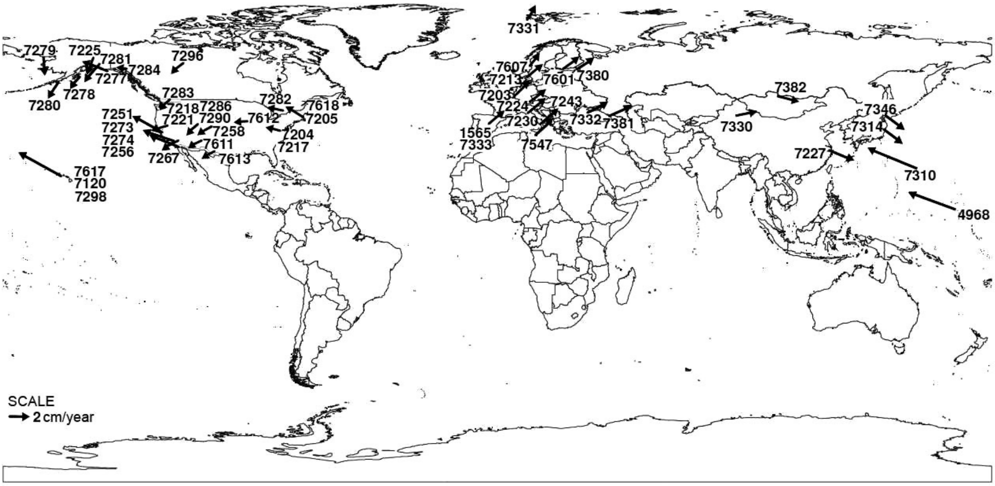

Fig. 3. Velocity vectors of the stations used in the solution.

height component; it can be due to a short observation period. It has an impact on accuracy estimation of plate motion parameters. Velocities of the other stations have formal errors of less than 1 millimetre per year. The absolute station velocities indicate the motion of the European part of plate in the northeast direction between 24–30 mm/yr, given in the ITRF2008. In our sequential solution the first step was performed for two stations located in northern and central Europe. Next, more stations were added one by one, as it is shown in Table 1. The final adjusted parameter values for nineteen antennas equal to $\Phi = 55.32° \pm 0.71°$, $\Lambda = 264.19° \pm 0.62°$, $\omega = 0.267°/\text{Ma} \pm 0.005°/\text{Ma}$ are given in Table 1 and in Figs. 4a, 4b, 4c. Stability of the solution is observed for 12 stations.

Table 1. Plate motion parameters estimated for the EUAS plate.

EURASIAN PLATE				
Number	Station name and ID number	Φ [°]	Λ [°]	ω [°/Ma]
2	Ny Alesund 7331 + Svetloe 7380	54.62 ± 1.51	259.27 ± 1.08	0.233 ± 0.012
3	(2) + Medicina 7230	56.13 ± 1.51	262.12 ± 1.08	0.267 ± 0.012
4	(3) + Urumqi 7330	56.77 ± 1.68	263.14 ± 1.16	0.267 ± 0.013
5	(4) + Shanghai 7227	57.21 ± 1.51	264.47 ± 1.00	0.283 ± 0.010
6	(5) + Mizusawa 7314	57.07 ± 1.68	264.22 ± 1.11	0.283 ± 0.011
7	(6) + Shintotsukawa 7346	57.04 ± 1.52	264.25 ± 1.01	0.283 ± 0.009
8	(7) + Matera 7243	55.05 ± 1.52	264.35 ± 1.012	0.283 ± 0.009
9	(8) + Simeiz 7332	55.05 ± 1.19	264.78 ± 0.84	0.283 ± 0.008
10	(9) + Zelenchukskaya 7381	55.49 ± 1.12	264.76 ± 0.78	0.283 ± 0.007
11	(10) + Madrid 1565	54.93 ± 1.03	264.00 ± 0.74	0.267 ± 0.007
12	(11) + Trysil 7607	54.97 ± 0.98	264.74 ± 0.71	0.267 ± 0.007
13	(12) + Onsala 7213	55.65 ± 0.93	264.42 ± 0.73	0.267 ± 0.006
14	(13) + Metsahovi 7601	55.23 ± 0.89	264.41 ± 0.70	0.267 ± 0.006
15	(14) + EFfelsberg 7203	55.24 ± 0.84	264.38 ± 0.68	0.267 ± 0.006
16	(15) + Wettzell 7224	55.32 ± 0.77	264.29 ± 0.66	0.267 ± 0.006
17	(16) + Badary 7382	55.33 ± 0.74	264.20 ± 0.64	0.267 ± 0.005
18	(17) + Yebes 7333	55.32 ± 0.71	264.19 ± 0.62	0.267 ± 0.005
19	(18) + Noto 7547	55.32 ± 0.71	264.19 ± 0.62	0.267 ± 0.005

Most of the VLBI antennas are located on the NOAM plate. They are not distributed uniformly; the majority of them are located in the western part of the NOAM plate near the boundary between the PACF and NOAM plates. Part of the plate's boundary is located in North America. Due to that fact, seven antennas which are located in North America but on the PACF plate have velocity vectors which agree with the motion of the PACF plate as exemplified by Monument Peak 7274, Point Reyes 7251, Pasadena 7263, Palos Verdes 7268, Santa Paula 7255. Thus, these antennas should be included in the solution for the PACF plate and not for the NOAM plate; otherwise it would result in very big errors of estimation of Φ, Λ, ω parameters. For the NOAM plate we used the following 28 stations in our study: St John's (7625), Yellowknife (7285), Hancock (7618), Greenbank (7204), Fairbanks (7225), Fort Davis (7613), North Liberty (7612), Platteville (7258), Pietown (7234), Los Alamos (7611), Penticton (7283), Whitehorse (7284), Sourdough (7281), Yakataga (7277), Kodiak (7278), Nome (7279), Quincy (7221), Algonquin (7282) and Westford

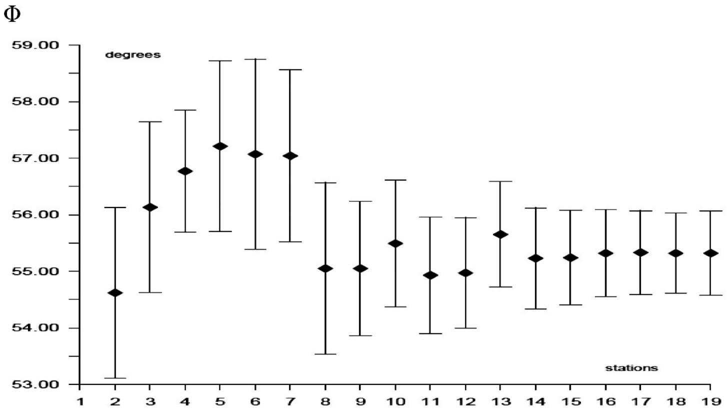

Fig. 4a. The Φ parameter estimated for the EUAS plate.

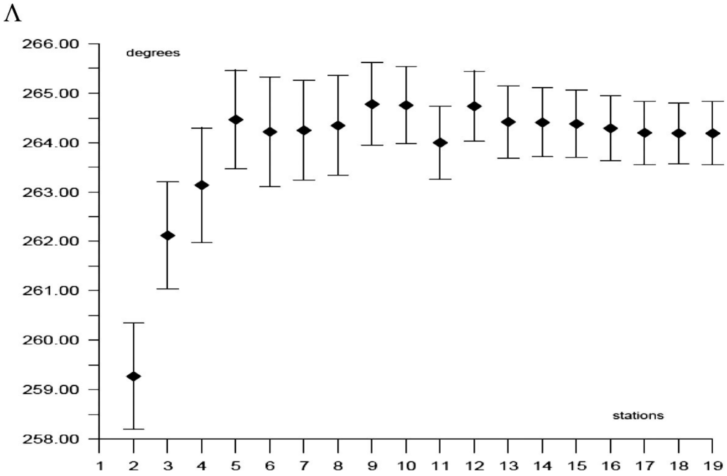

Fig. 4b. The Λ parameter estimated for the EUAS plate.

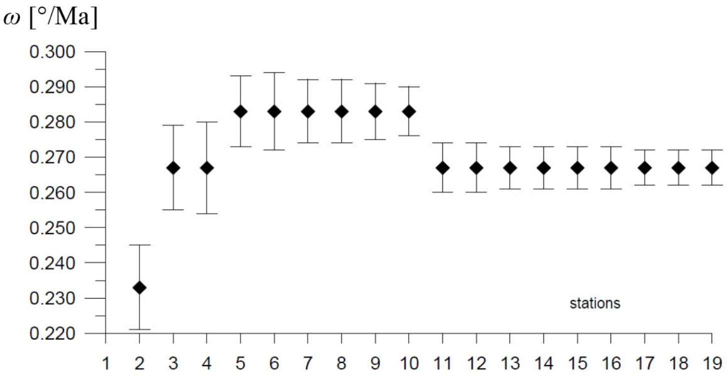

Fig. 4c. The ω parameter estimated for the EUAS plate.

(7209), Hat Creek (7218), Maryland Point (7217), Vernal (7290), Sandpoint (7280), Black Butte (7259), Deadman Lake (7267), Ely (7286), Mammoth Lakes (7259) and Shirleys Bay (7626). Stability was reached for about 12 stations. The final result is equal to $\Phi = -5.13° \pm 0.77°$, $\Lambda = 274.32° \pm 0.31°$, $\omega = 0.183°/\text{Ma} \pm 0.004°/\text{Ma}$, as shown in Table 2 and in Figs 5a, 5b, 5c.

Table 2. Plate motion parameters estimated for the NOAM plate.

NORTH AMERICAN PLATE				
Number	Station name and ID number	Φ [°]	Λ [°]	ω [°/Ma]
2	St John's 7625 + Yellowknife 7296	1.49 ± 1.53	275.10 ± 0.41	0.200 ± 0.005
3	(2) + Hancock 7618	−2.13 ± 1.05	275.50 ± 0.37	0.183 ± 0.004
4	(3) + Greenbank 7204	−2.45 ± 1.02	274.95 ± 0.37	0.183 ± 0.004
5	(4) + Fairbanks 7225	−2.01 ± 1.02	276.41 ± 0.42	0.200 ± 0.004
6	(5) + Fort Davis 7613	−1.75 ± 1.45	276.08 ± 0.64	0.183 ± 0.006
7	(6) + Nort Liberty 7612	−1.95 ± 1.43	275.50 ± 0.60	0.183 ± 0.006
8	(7) + Platteville 7258	−1.95 ± 1.32	275.50 ± 0.55	0.183 ± 0.006
9	(8) + Pietown 7234	−3.90 ± 1.32	275.20 ± 0.57	0.183 ± 0.006
10	(9) + Los Alamos 7611	−5.08 ± 1.32	274.86 ± 0.57	0.183 ± 0.006
11	(10) + Pentiction 7283	−5.09 ± 1.24	274.86 ± 0.54	0.183 ± 0.006
12	(11) + Whitehorse 7284	−5.08 ± 1.18	274.86 ± 0.51	0.183 ± 0.005
13	(12) + Sourdough 7281	−5.07 ± 1.13	274.86 ± 0.49	0.183 ± 0.005
14	(13) + Yakataga 7277	−5.07 ± 1.09	274.87 ± 0.47	0.183 ± 0.005
15	(14) + Kodiak 7278	−5.08 ± 1.05	274.87 ± 0.45	0.183 ± 0.005
16	(15) + Nome 7279	−5.08 ± 1.01	274.87 ± 0.44	0.183 ± 0.005
17	(16) + Quincy 7221	−5.26 ± 1.01	274.50 ± 0.44	0.183 ± 0.005
18	(17) + Algonquin 7282	−5.30 ± 0.98	274.61 ± 0.44	0.183 ± 0.005
19	(18) + Westford 7205	−5.01 ± 0.91	274.32 ± 0.37	0.183 ± 0.004
20	(19) + Hat Creek 7218	−5.13 ± 0.92	274.30 ± 0.37	0.183 ± 0.004
21	(20) + Maryland Point 7217	−5.13 ± 0.89	274.30 ± 0.36	0.183 ± 0.004
22	(21) + Vernal 7290	−5.13 ± 0.89	274.30 ± 0.36	0.183 ± 0.004
23	(22) + Sandpoint 7280	−5.13 ± 0.85	274.30 ± 0.34	0.183 ± 0.004
24	(23) + Black Butte 7259	−5.13 ± 0.83	274.30 ± 0.34	0.183 ± 0.004
25	(24) + Deadman Lake 7267	−5.13 ± 0.81	274.30 ± 0.33	0.183 ± 0.004
26	(25) + Ely 7286	−5.13 ± 0.80	274.30 ± 0.32	0.183 ± 0.004
27	(26) + Mammoth Lakes 7259	−5.13 ± 0.78	274.30 ± 0.32	0.183 ± 0.004
28	(27) + Shirleys Bay 7626	−5.13 ± 0.77	274.30 ± 0.31	0.183 ± 0.004

For the PACF plate we used 12 stations: Point Reyes (7251), Pasadena (7263), Fort Ord (7266), Monument Peak (7274), Kauai (1311), Mauna Kea (7617), Maui (7120), Kwajalein Atol (4968), Minami Tori (7310), Santa Paula (7255), Palos Verdes (7268), Pinyon Flats (7256), located in North America, on Hawaii Islands and near Japan. Stability was obtained for about 10 stations. The final computation results of the plate parameters are equal to: $\Phi = 62.87° \pm 0.05°$, $\Lambda = 102.50° \pm 2.03°$, $\omega = 0.683°/\text{Ma} \pm 0.010°/\text{Ma}$. The steps of sequential solution are shown in Table 3 and in Figs 6a, 6b, 6c.

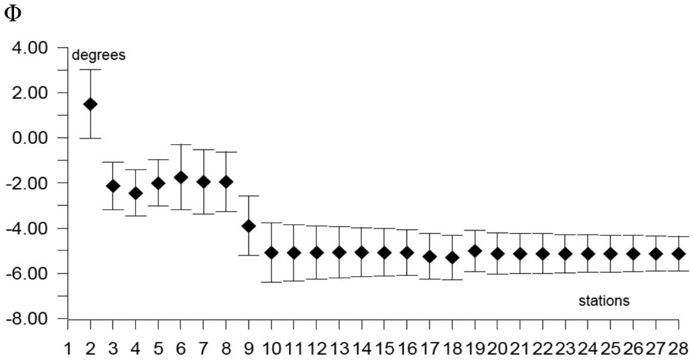

Fig. 5a. The Φ parameter estimated for the NOAM plate.

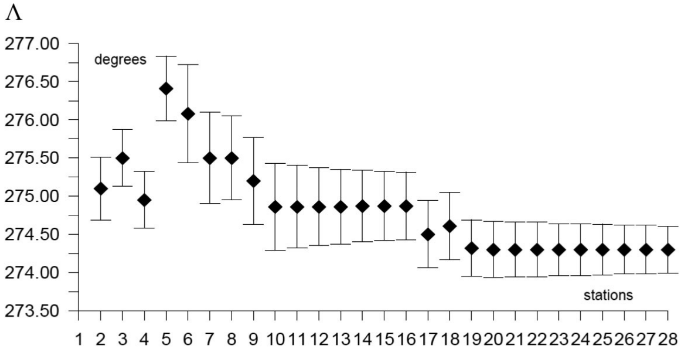

Fig. 5b. The Λ parameter estimated for the NOAM plate.

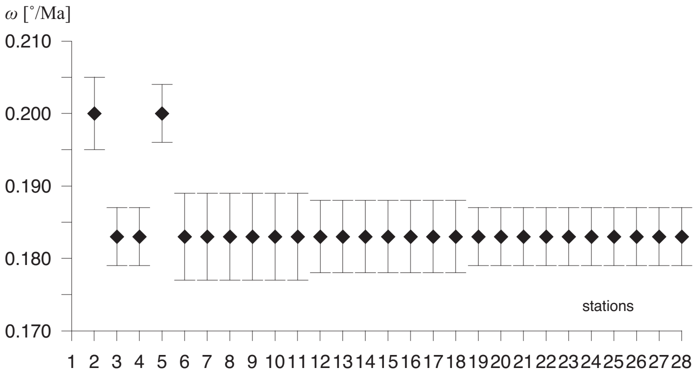

Fig. 5c. The ω parameter estimated for the NOAM plate.

For the AFRC plate only one station VLBI Hartebeesthoek (7232) was located in the southern part of Africa. A single station does not enable to estimate the Φ, Λ, ω parameters. Additional stations from another technique have to be included in the estimation.

Table 3. Plate motion parameters estimated for the PACF plate.

PACIFIC PLATE				
Number	Station name and ID number	Φ [°]	Λ [°]	*ω* [°/Ma]
2	Kauai 7311 + Maunakea 7617	−62.93 ± 0.12	102.86 ± 5.27	0.683 ± 0.021
3	(2) + Maui 7120	−62.88 ± 0.09	102.99 ± 4.92	0.683 ± 0.020
4	(3) + Minami Tori 7310	−62.89 ± 0.07	102.92 ± 3.76	0.683 ± 0.015
5	(4) + Kawajalein Atoll 4968	−62.86 ± 0.08	103.35 ± 2.78	0.683 ± 0.015
6	(5) + Point Reyes 7251	−62.98 ± 0.05	102.85 ± 2.77	0.683 ± 0.011
7	(6) + Pasadena 7263	−62.20 ± 0.05	102.95 ± 2.63	0.700 ± 0.011
8	(7) + Fort Ord 7266	−62.86 ± 0.05	102.62 ± 2.43	0.683 ± 0.011
9	(8) + Santa Paula 7255	−62.89 ± 0.05	102.53 ± 2.28	0.683 ± 0.010
10	(9) + Palos Verdes 7268	−62.89 ± 0.05	102.50 ± 2.24	0.683 ± 0.010
11	(10) + Pinyon Flats 7256	−62.87 ± 0.05	102.50 ± 2.15	0.683 ± 0.010
12	(11) + Monument Peak 7274	−62.87 ± 0.05	102.50 ± 2.03	0.683 ± 0.010

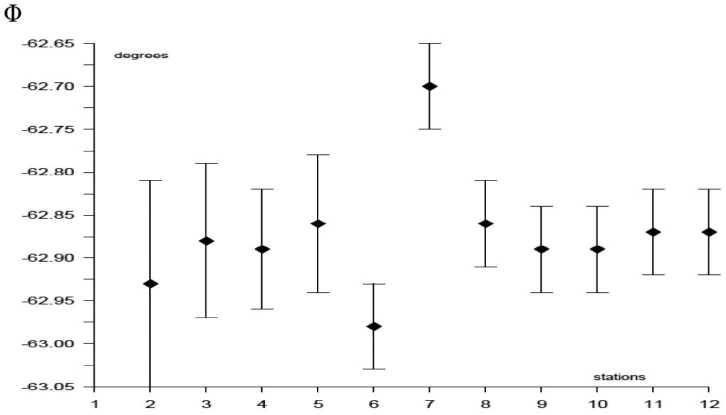

Fig. 6a. The Φ parameter estimated for the PACF plate.

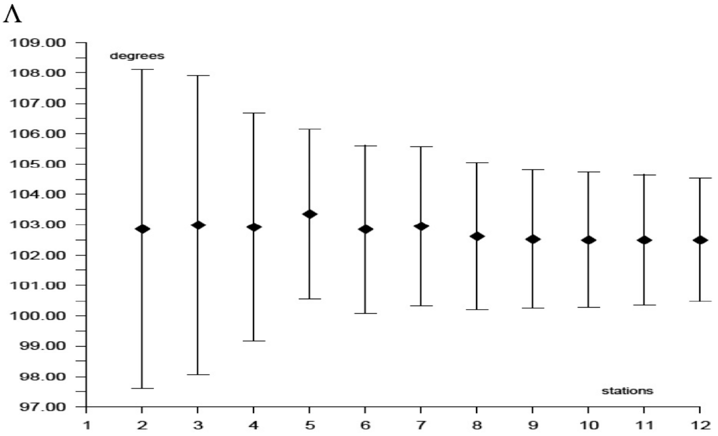

Fig. 6b. The Λ parameter estimated for the PACF plate.

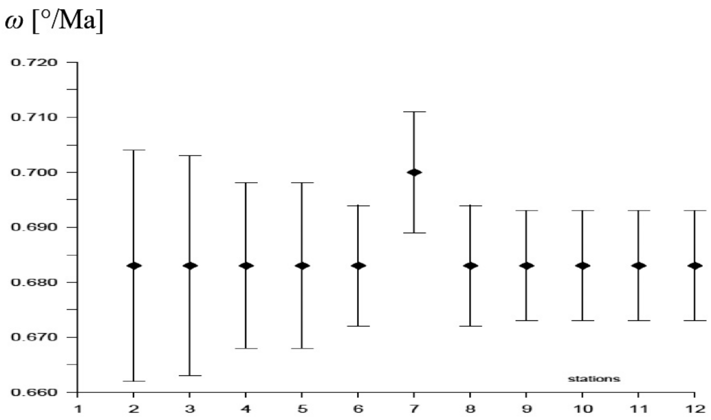

Fig. 6c. The ω parameter estimated for the PACF plate.

For the AUS plate two stations located in the continent were used: Tidbinbilla (1545), Parkes (7202) and one station Hobart (7242) located on the island of Tasmania; the distance between the stations is very small, not exceeding 200 km, thus it has a negative influence on the accuracy of estimation. The final values of Φ, Λ, ω parameters are equal to: $\Phi = 32.63° \pm 0.20°$, $\Lambda = 37.41° \pm 0.39°$, $\omega = 0.617°/\text{Ma} \pm 0.005°/\text{Ma}$. Despite a limited quantity of stations located on the plate and a small distance between them we were able to obtain small errors and good consistency with the APKIM2005 model. The results are shown in Table 4.

Table 4. Plate motion parameters estimated for the AUS plate.

AUSTRALIAN PLATE				
Number	Station name and ID number	Φ [°]	Λ [°]	ω [°/Ma]
2	Tidbinbilla 1545 + Parkes 7202	34.11 ± 0.20	32.73 ± 0.65	0.667 ± 0.009
3	(2) + Hobart 7242	32.63 ± 0.20	37.41 ± 0.39	0.617 ± 0.005

For the ANTC plate there are only two stations located on the plate: Syowa (7342) and O'Higgins (7245). It enables to estimate plate motion parameters, but no adjusted solution. The final values are shown in Table 5 and are equal to: $\Phi = 59.21° \pm 0.75°$, $\Lambda = 232.35° \pm 1.98°$, $\omega = 0.216°/\text{Ma} \pm 0.002°/\text{Ma}$. In spite of this fact, a good consistency with the APKIM2005 model is observed. Only for parameter Λ the difference is equal to 7 degrees. It is due to geographical latitude of the plate greater than 70 degrees. The distance equal to 7 degrees for 70 degree or greater parallel is significantly smaller than for mean latitude.

Table 5. Plate motion parameters estimated for the ANTC plate.

ANTARCTIC PLATE				
Number	Station name and ID number	Φ [°]	Λ [°]	ω [°/Ma]
2	Syowa 7342 + O'higgins 7245	59.21 ± 0.75	232.35 ± 1.98	0.216 ± 0.002

The final estimations of values of Φ, Λ, ω parameters for the EUAS, AUS, NOAM, PACF and ANTC plates based on the VLBI technique are shown in Table 6 and compared with the

APKIM2005 model [6] on the basis of the common solution for all the techniques (DORIS, SLR, GPS, VLBI). For this reason the errors of the estimated parameters are smaller. Our results given in Table 6 can be compared with the results obtained by Kraszewska *et al*. [10] for SLR technique and Kraszewska *et al.* [11] for DORIS technique.

Table 6. The values of Φ, Λ, ω parameters estimated for the EUAS, NOAM, AUS, PACF and ANTC plates based on the VLBI technique and model parameters (APKIM2005).

Estimated					**APKIM2005 Model**
Number of stations	Plate	Φ [°]	Λ [°]	ω [°/Ma]	Φ [°], Λ [°], ω [°/Ma]
19	EUAS	55.32 ± 0.71	264.19 ± 0.62	0.267 ± 0.005	53.4 ± 0.4, 264.3 ± 0.5, 0.259 ± 0.001
28	NOAM	−5.13 ± 0.77	274.32 ± 0.31	0.183 ± 0.005	−4.3 ± 0.6, 275.8 ± 0.2, 0.194 ± 0.002
3	AUS	32.63 ± 0.20	37.41 ± 0.39	0.617 ± 0.005	32.8 ± 0.1, 36.7 ± 0.3, 0.639 ± 0.002
12	PACF	−62.87 ± 0.07	102.50 ± 2.03	0.683 ± 0.010	−63.2 ± 0.1, 110.5 ± 0.5, 0.67 ± 0.002
2	ANTC	59.28 ± 0.75	232.35 ± 1.98	0.216 ± 0.002	61.1 ± 0.5, 239.5 ± 0.7, 0.243 ± 0.004

5. Conclusions

Based on the carried out research the following can be concluded:

- For each tectonic plate a uniform distribution of stations is recommended. Location of a large number of stations within a small-sized area does not lead to a significant increase of solution accuracy. This case is observed along the boundary between the western part of NOAM plate and the PACF plate.
- The VLBI stations are not uniformly distributed over the Earth. The highest density of stations is found only for three plates: EUAS (20 antennas), NOAM (30 antennas) and PACF (12 antennas). Stability of solutions and high accuracy are observed on the EUAS and NOAM plates for about 12 stations, and on the PACF plate for 10 stations. It is shown in Figs 4a, 4b, 4c, 5a, 5b, 5c, 6a, 6b, 6c, respectively. It proves that only the number of VLBI stations distributed over the EUAS or NOAM and PACF plates is sufficient for estimation of tectonic plate parameters with a high accuracy. It is recommended to monitor continuously station displacement, particularly for boundaries between plates. It is observed for the boundary between the PACF plat and the western part of NOAM plate. In the case of these stations, velocities should be treated as unknown in the estimation of station positions and velocities. For a few stations distributed over North America, velocity vectors agree better with the PACF plate. An example of this are the following stations: Monument Peak 7274, Pasadena 7263, Pinyon Flats 7256, Point Reyes 7251, Fort Ord 7266, Palos Verdes 7268, Santa Paula 7255. These stations are used for the PACF plate motion estimation.
- The calculated plate motion parameters were compared with those of the APKIM2005 model. A very good consistency of results with the APKIM2005 model is observed for the EUAS, NOAM and the AUS plates. The discrepancies are of an order of 2 degrees. For the NOAM and EUAS plates there was obtained stability of motion parameter values and their errors for 12 stations, as well as for approximately 10–12 stations of the PACF plate.
- For the AFRC plate there is only 1 station located on the plate; it does not enable to estimate three parameters of plate motion and to apply the sequential solution to analysis of solution stability of the plate.

- For the ANTC plate there are only 2 stations located on the plate. It enables to estimate plate motion parameter values, but not an adjusted solution. Despite this, a good consistency with the APKIM2005 model is observed; only for Λ parameter the difference is equal to 7 degrees. It is caused by the geographical position of the plate (near the pole). The distance equal to 7 degrees for 70 degree or greater parallel is significantly smaller than for mean latitude. For the PACF plate the conclusion is similar.
- For the AUS plate, there are 3 stations located on the plate. The estimation of Φ, Λ, ω parameter values is possible, but stability cannot be adjusted using the sequential solution, particularly because the stations are not uniformly distributed (three stations are concentrated within a very small region). Increasing the number of stations on the AUS plate is recommended. Nevertheless, the estimated Φ, Λ, ω parameter values are closely consistent with those of the APKIM2005 model, and their errors are very small.

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